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Auroral spectral intensities by eletron impact excitation

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In this paper the total ionization, N_2^+, O_2^+ and O^+ ions produced by flux of nonenergy precipitating electrons in the auroral region atmosphere are studied for 1 KeV and 10 KeV incident energies. Using the laboratory measured cross-sections for N_2^+ ING, O_2^+ING, and NII permitted lines and theoretically estimated value for λ5577 OI green line, estimates are made of the total number of photons produced in above spectral bands and lines due to the precipitating electrons. The present results have also been compared with other theoretical and experimental results for auroral spectral intensitis.

1. INTRODUCTION

Attempts have been repeatedly made to estimate the ionization and the excitation by the impact of energetic electrons precipitatng into the earth's atmosphere. Among these the results of Rees (1963), Kamiyama (1967) and Stolarski and Green (1967) are widely referred in literature. Their approach for the derivation of ionization and excitations by electrons are different. Rees (1963) and Kamiyama (1967) have taken standard atmosphere while, Stolarski and Green (1967) used an atmosphere with a standard mixture of N_2, O_2 and atomic oxygen. Former two authors have assumed that the total ionization cross-section of N_2, O_2 and O are equal in values. However, the measurements of Fite and Brackamann (1959) do not justify such assumption. A more realistic approach would be that the total ionization cross-section of O_2 is nearly equal to that of N_2 and twice the ionization cross-section of atomic oxygen. Also, in these computation the efficiency of atomic oxygen. Also, in these computation the efficiency of (0, 0) N_2^+ first negative band (ING) was taken only as 2% while later laboratory measurements (Srivastava and Mirza 1968; Borst and Zipf 1969; Hartmann 1968; Aarts *et al* 1968) puts the value close to 6.6%. Stolarski and Green (1967) in their computation have taken a lower value for the $B^2\overset{+}{\underset{u}{\Sigma}}$ (N_2^+) level excitation cross-section. This has also resulted in comparatively higher intensity for OI (λ5577) green line in compaiison to N_2^+ (ING) bands.

In this paper, using the latest atmospheric model, excitation cross-sections and efficiencies of important nitrogen and oxygen bands and lines, the ionization and excitation by energetic electrons in the earth's atmosphere have been computed. Also, the intensities of important atomic lines and molecular bands excited by precipitating electron have been derived.

2. Ionization and energy deposition by electrons

It is generally accepted that the auroral luminosity and ionization are mainly produced by streams of electrons. The incoming electrons lose energy mainly by ionizing the neutral atmospheric constituents (although the portion of energy going into other processes, such as heating is not completely known). Grün (1957) in a laboratory experiment measured the range of electrons in air for 5 to 54 KeV energy. Using this value and other available data Rees (1964) plotted a curve for μ the rangeenergy relation. Grun (1957) estimated the fractional energy loss $\lambda[Z/R]$ for various $[Z/R]$ values in his experimental work, R being the range of electron in mg/cm^2 and Z the partial range in the same units. The values of $\lambda[Z/R]$ for any value between 0 to 1 of $[Z/R]$ are available. Some of the incoming electrons reverse their paths while penetrating into the atmosphere (this fraction is somewhere between 0 to 15%). The value of $\lambda[Z/R]$ for negative values of $[Z/R]$ due to reflection has also been computed by Grün (1957). Using the experimental value $\lambda[Z/R]$ and R given by Grun (1957) and Rees (1963, 1964) the total ionization due to a precipitating electron at different altitudes can be given (c.f. Rees 1963) as

$$Q_Z = \frac{E_0/r_0}{\Delta_e} \lambda \left[\frac{Z}{R}\right] \frac{n(M)_Z}{n(M)_R}, \qquad \dots \quad (1)$$

where Q_Z is total ionization at any altitude Z, E_0 is the initial energy of electron in eV, r_0 is the density scale height in cm at the lowest altitude of penetration of the electron, Δ_e is the mean energy loss per ionization, $n(M)_Z$ and $n(M)R$ are the total number of ionizable molecules at depth Z and the lowest altitude of penetration, respectively. In this calculation $b(M)$ has been taken equal to $n(N_2)$ $+N(O_2)+\frac{1}{2}n(O)$ at any altitude assuming ionization cross-section of $N_2 \simeq$ that of $O_2 \simeq$ twice that of atomic oxygen and $n(N_2)$, $n(O_2)$ and $N(O)$ are the concentrations of nitrogen, oxygen and atomic oxygen, respectively. The effects of other minor constituents are negligible for $n(M)$ value. The value of Z at various altitudes is equal to the pressure at that altitude in *mg/cm*^{2}. R is the range of electron in mg/cm^2 and its numerical value is equal to the pressure at the lowest altitude of penetration. The value of R was taken from Grün (1957) and Rees (1964) and the value of Δ_e has been taken 32 eV. The values of $\lambda[Z/R]$ for monodirectional as well as isotropic angular distribution for various values of $[Z/R]$ have been taken from the plot given by Rees (1963). In the present investigation the atmospheric model was taken from Jacchia (1971) model for $T_\alpha = 1700°$K. In Figs 1-4, the total ionizations produced by 1 KeV and 10 KeV electrons for the monodirectional and isotropic (0–70°) angular distribution are given. Also, the production of N_2^+, O_2^+ and O^+ ions are plotted separately in these figures. The isotropic distribution has provided the broader profile in comparison to monodirectional (vertically down) incoming electrons. Rees (1964) calculation in which earth's magnetic field effect was taken into consideration did not alter the general nature of the total ionization produced when the magnetic field effect was neglected This is mainly due to the fact the most of the electron's energy is lost in a layer close to the minimum height of penetration and any difference in paths of the two cases is only marginal.

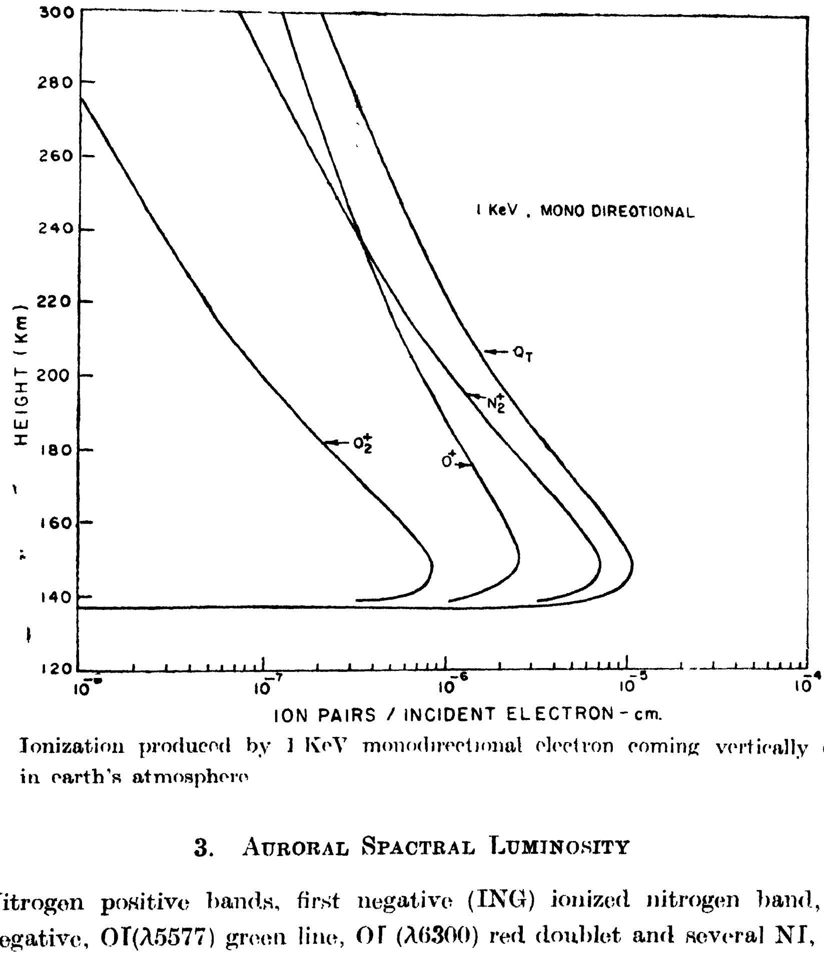

Fig. 1. Ionization produced by 1 KeV monodirectional electron coming vertically down in earth's atmosphere

3. Auroral Spactral Luminosity

Nitrogen positive bands, first negative (ING) ionized nitrogen band, O_2^+ first negative, OI(λ5577) green line, OI (λ6300) red doublet and several NI, NII, OI permitted lines are the main spectral features of the auroral luminosity. Cross-sections for the total ionization of N_2 and the level excitation of N_2^+ $(B^2 \overset{+}{\underset{u}{\Sigma}})$ from the ground state of neutral N_2 molecules have been measured by several groups. The recent measurements of $B^2 \overset{+}{\underset{u}{\Sigma}}$ state cross-section indicate that approximately one photon of N_2^+ (ING) (0, 0) radiation at λ3914Å is emitted per $16N_2^+$ ion pairs formed. The fluorescence efficiency measured by Hartmann (1968) also justifies this estimation assuming that 35 eV energy is lost per ion pair formation by the electron. Under this condition the volume emission rate for λ 3914Å per electron-cm can be expressed as :

$$\eta(\lambda 3914) = 0.066 \frac{E_0/r_0}{\Delta_e} \lambda[Z/R] \frac{n(N_2)_Z}{n(M)_R}$$

combining the above relation with eq. (1) we get

$$\eta(\lambda\, 3914) = 0.066\ Q_Z \frac{n(N_2)_Z}{n(M)_Z} \qquad \ldots \quad (3)$$

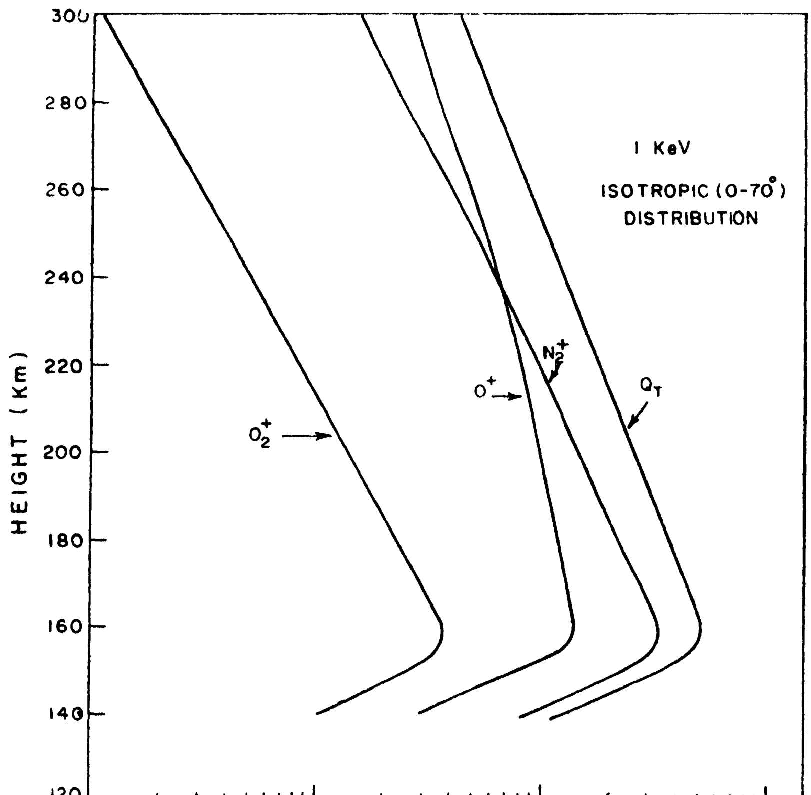

Fig. 2. Ionization produced by 1 KeV electron streams having angular distribution of 0—70° in earth's atmosphere.

Fig. 5 shows the illustrative curves for the luminosity profiles of λ 3914Å (0, 0) N_2^+ (ING) produced by monodirectional and isotropic angular distribution (0-70°) electrons of initial energies of 1 KeV and 10 KeV. In isotropic distribution nearly 15.4 photons of λ 3914 are produced by an electron of 10 KeV initial energy. Nearly 80% of the emission is confined into a vertical height of 10 km (between 102-112 km) above the lowest height of penetration.

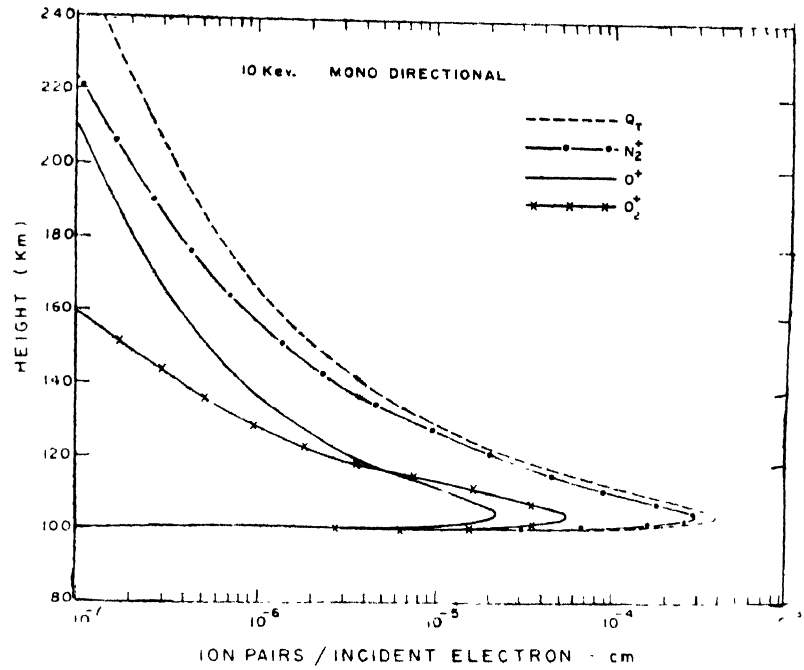

Fig. 3. Ionization produced by 10 KeV monodirectional electron in earth's atmosphere.

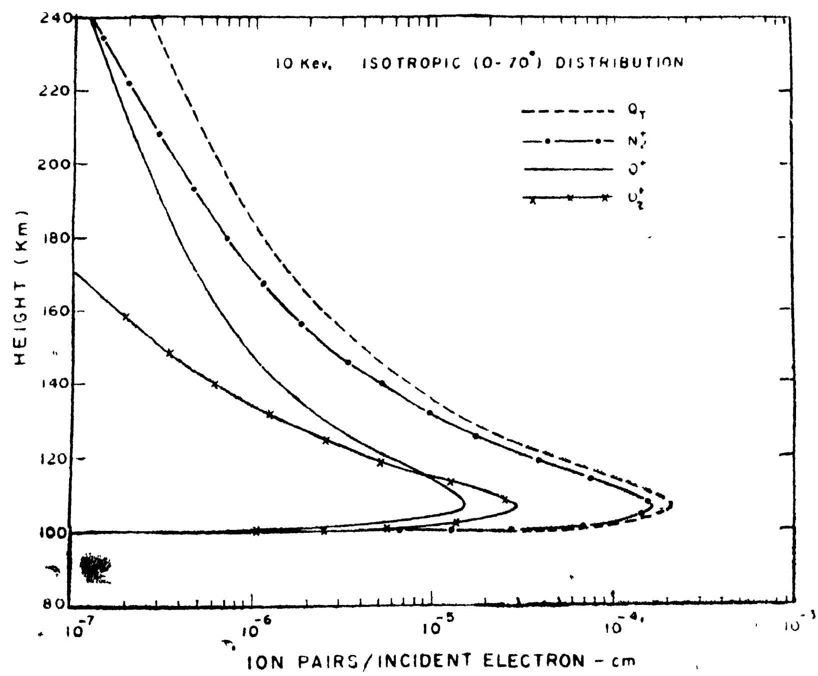

Fig. 4. Ionization produced by 10 KeV electron streams having angular distribution of 0.70° in earth's atmosphere.

The OI green line λ 5577 is another prominent feature of the auroral spectrum. This line is excited directly from the ground state $O(3p)$ of the oxygen atom by low energy secondary electrons :

$$\begin{aligned} & O(^3P)+e \rightarrow O(^1S)+e \\ & O(^1S) \rightarrow h\nu\,(\lambda 5577)+O(^1D) \end{aligned} \qquad (4)$$

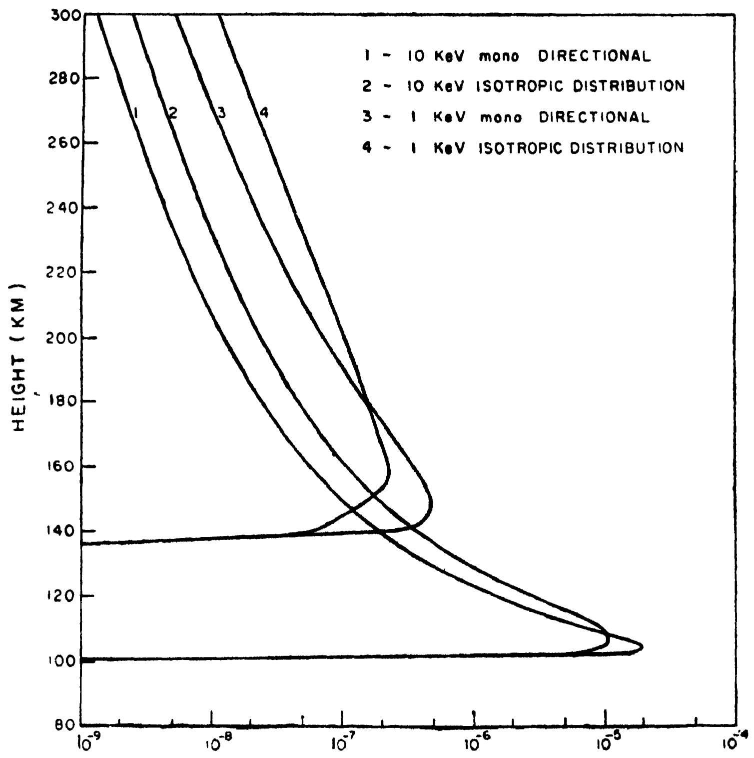

Fig. 5. Excitation rate of λ3914 radiation by 1 KeV and 10 KeV monodirectional and isotropic (0—70°) streams of electrons.

The oxygen green line is also excited by dissociative recombination of O_2^+ ions with electrons :

$$\begin{aligned} & O_2^+ + e \rightarrow O(^1S)+O^+ + e \\ & \qquad \text{or} \\ & O(^1S)+O+e+e \end{aligned} \qquad \ldots \quad (5)$$

The equilibrium number density $R(O_2^+)$ of O_2^+ ions can be expressed by a chemical equilibrium equation taking into consideration. The first four dominant reaction given in Table 1.

$$R(O_2^+) = Q_Z \left[\frac{n(O_2)}{n(M)} + \frac{\frac{1}{2}n(O)}{n(M)} \left\{ 1 + \frac{\alpha_1 n(N_2)}{\alpha_2 n(O_2)} \right\}^{-1} + \frac{n(N_2)}{n(M)} \left\{ 1 + \frac{\alpha_3 n(O)}{\alpha_4 n(O_2)} \right\}^{-1} \right]$$

where Q_Z is total ionization, α_1, α_2, α_3 and α_4 are the reaction rate coefficients of the reactions 1-4, respectively and their values are given in Table 1. Other factors of eq. (6) have been explained earlier in the text. The concentration of O_2^+ ions is quite insensitive to the dissociative recombinations of N_2^+, O_2^+ and NO^+ (reactions 5-7 listed in Table 1).

Night glow measurements indicate that approximately one photon of OI $\lambda6300$ is produced for every 10 dissociative recombinations of O_2^+ ions and one photon of $\lambda5577$ is produced for every 5 photons of $\lambda6300$ [c.f. Rees *et al* (1967)].

Table 1. Rate coefficients

S. No.	Reaction	Rate coefficient (cm^3sec^{-1})	Reference
1.	$O^+ + N_2 \rightarrow NO^+ + N$	$\alpha_1 = 3.0 \times 10^{-12}$	Ferguson *et al* (1965a, b)
2.	$O^+ + O_2 \rightarrow O_2^+ + O$	$\alpha_2 = 4.0 \times 10^{-11}$	Fehsenfeld, Golden, Schmeltekopf and Ferguson (1965)
3.	$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	$\alpha_3 = 1.0 \times 10^{-10}$	Fehsenfeld, Schemeltakopt and Ferguson (1965a)
4.	$N_2^+ + O \rightarrow NO^+ + N$	$\alpha_4 = 2.5 \times 10^{-10}$	
5.	$O_2^+ + N_2 \rightarrow NO^+ + NO$	$\alpha_5 = 1 \times 10^{-15}$	
6.	$N_2^+ + e \rightarrow N' + N'$	$\alpha_6 = 2.8 \times 10^{-7}$	Kasner and Biondi (1965)
7.	$O_2^+ + e \rightarrow O' + O'$	$\alpha_7 = 1.7 \times 10^{-7}$	Biondi (1964)
8.	$NO^+ + e \rightarrow N + O$	$\alpha_8 = 5.0 \times 10^{-7}$	

Therefore, the photon emission $\eta_R(\lambda5577)$ due to dissociative recombination of O_2^+ will be 2% of the equilibrium concentration of O_2^+ ions i.e.

$$\eta_R(^1S) = 0.02R(O_2^+) \text{ cm}^{-3}\text{sec}. \qquad \dots (7)$$

The direct excitation of $O(^1S)$ state from the ground state of atomic oxygen due to secondary electrons in eq. (5) can be expressed as :

$$\eta_D(^1S) = \alpha n_e n(O) \text{ cm}^{-3}\text{sec}^{-1}, \qquad \dots (8)$$

where α is the rate coefficient of eq. (5), n_e is the number density of equilibrium electrons and $n(O)$ is the concentration of atomic oxygen. Assuming the neutrality of the atmosphere above 80 km, the total ions $Q_Z = n_e$ at any altitude above 80 km.

Assuming this, eq. (8) can be expressed as :

$$\eta_D(^1S) = \alpha Q_Z n(O)\ \mathrm{cm}^{-3}\mathrm{sec}^{-1}$$

According to Takayangi and Yonezawa (1961) the value of α is approximately equal to 0.3. In Fig. 6 the value of $\eta_R(^1S)$ (excitation of λ5577 due to dissociative

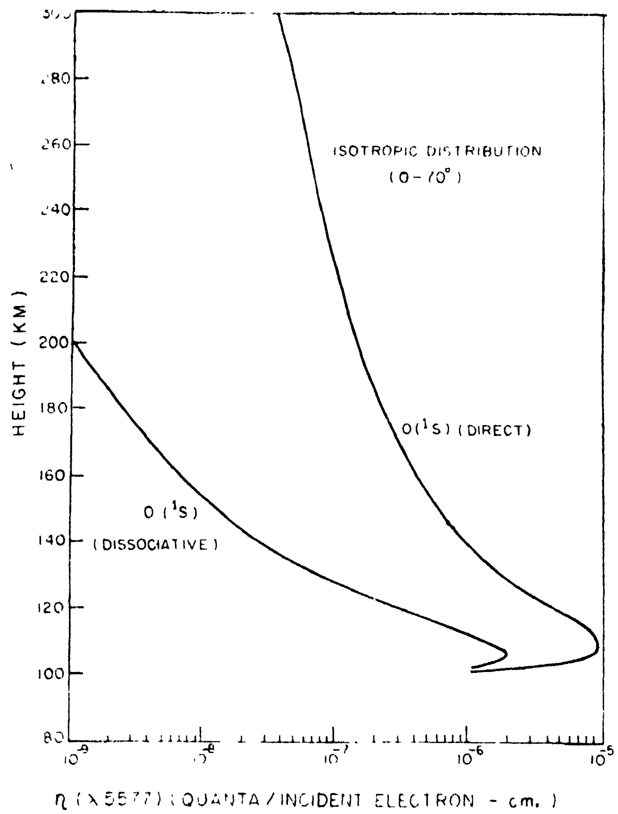

Fig. 6. Excitation rate of λ 5577 radiation produced by 10 KeV isotorpic (0—70°) streams of electrons.

recombination) and $\eta_D(^1S)$ due to direct excitation has been plotted for 10 KeV electrons having isotropic angular distribution(0—70°). The integrated photon emission of λ5577 due to direct excitation is 21 photons/electron and 2.3 photons/electron due to dissociative recombination processes. Assuming the quenching of $O(^1S)$ negligible in the height region under consideration, and other assumptions from airglow intensity and dissociative recombination are justifiable, the total photoemission of 5577Å due to a 10 KeV electron would be approximately 23.3 quanta/electron.

Similar to N_2^+ first negative bands, O_2^+ 1st negative and 2nd negative bands are excited by direct ionization and excitation of O_2 by electron impact. The excitation cross-section of $b^4\Sigma_g$ state of O_2^+, the upper state of 1st negative band of O_2^+ is about 8.2% of the total ionization cross-section of O_2 (Srivastava 1970, 1974) from 0.1 KeV to higher energies. Taking this constant factor for all the energies, a 10 KeV electron with isotropic angular distribution (0-70°) will produce 3.4 photons/electron.

Srivastava (1969) in a controlled laboratory experiment determined the excitation cross-section of NI permitted lines (λλ5001-5006, 5667 & 5680Å) due to electron impact on nitrogen gas. The relative intensities of these three lines were 100 : 30 : 76 respectively. Also he found that the total emission cross-section of λ5001-5006Å NII line is nearly a constant fraction (~0.18%) of the total ionization of N_2 and (0.85±0.09) per cent of the N^+ (K.E. > 0.25 eV) formed by the dissociative ionization of N_2 by electron. Taking this observation into consideration the emission of NII lines produced by 10 KeV electron are listed in Table 2. Also for comparison, results of other investigators are given in the table.

Table 2 Intensity of auroral emission in KR

Transitions (wave length)	Experimental Hunten (1955)	Theoretical Stolarski and Green (1967)	Present results by 10 KeV isotropically (0-70°) distributed electron
$B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ (0, 0)(N_2^+ ING) λ3914	100	100	100
$b^4\Sigma_g \rightarrow a^4\pi_u$ O_2^+ING		156	20
$O^1S \rightarrow O^1D$ λ5577 OI	130	376	151
$3d^3F^0 \rightarrow 3p^3D$ λ5001-5006 NII	0.96		2.3
$3p^3D \rightarrow 3S^3P^0$ λ5667 NII			0.7
$3p^3D \rightarrow 3S^3P^0$ λ5680 NII			1.75

In the table the photon emission is normalised to λ3914 (0, 0) N_2^+ (ING) band of 100 KR emission corresponding to IB.C.III standard auroral luminosity.

the differential cross sections for the scattering of electrons from hydrogen and helium atoms were calculated in this approximation using

$$V_{eff}(r) = V_{00}(r) - \frac{\alpha}{(r^2+r_0^2)^2} \quad \ldots \quad (2)$$

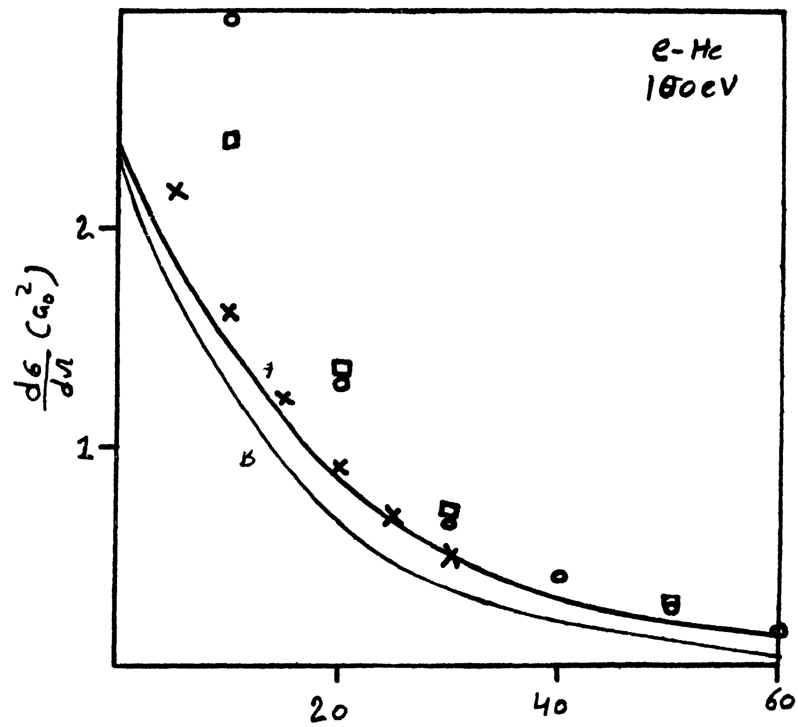

Fig. 1. Differential cross sections for the elastic scattering of electrons from hydrogen and helium atoms. Present calculations Curve A, calculations of Saha *et al* (1973)—Curve B, experimental data of Teubner and Lloyed (1974) —● for e^-–H scattering; experimental data of Crooks and Rudd (1973) - □, of Sethuraman *et al* (1972)—O, of Vriens (1968)—× as normalized by Chamberlain (1970)x for the e^-—He scattering.

in eq. (1) to see if the agreement with experiment improves at the forward angles. Here V_{00} is the static potential which in the case helium atom was calculated using for the ground state a somewhat better normalized Hartree-Fock wavefunction (Byron and Joachain 1966)

$$\psi_0(r_1, r_2) = \phi(r_1)\,\phi(r_2) \quad \ldots \quad (2)$$

where

$$\phi(r) = N[e^{-\alpha r} + Ce^{-\beta r}]$$

with

$$N = \sqrt{\frac{1.6966}{\pi}}\;;\; \alpha = 1.41;\;\; \beta = 2.61 \text{ and } C = 0.799$$

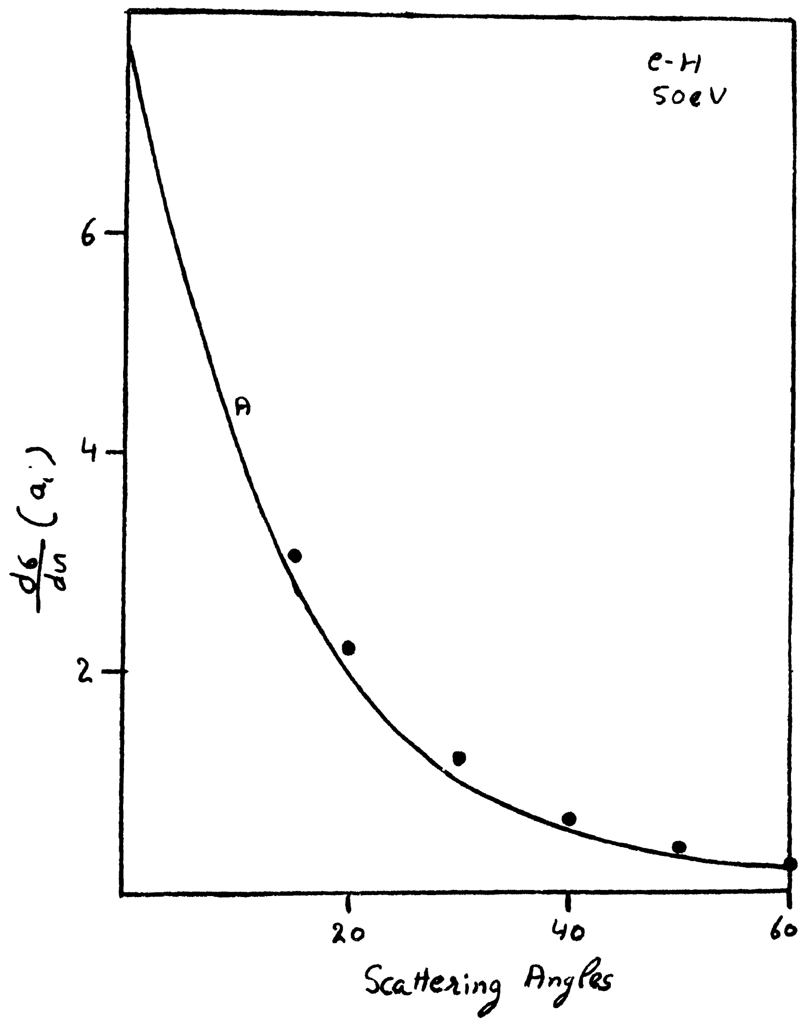

Fig. 1b

On performing the integrals for V_{eff} analytically in eq. (1) the expressions for the scattering amplitudes for hydrogen and helium atoms can be written as

$$f_H(\theta) = -ik \int_0^\infty bJ_0(qb) \left[\exp\left(\frac{i}{k}\left\{2bK_1(2b)+2K_0(2b)+\frac{\alpha\pi}{4(r_0^2+b^2)^{3/2}}\right\}\right)-1\right]db \qquad \dots \quad (4)$$

and

$$f_{He}(\theta) = -ik \int_0^\infty bJ_0(qb) \left[\exp\left(\frac{i}{k}\left\{32N^2\pi \left(\frac{1}{(2\alpha)^3}K_0(2\alpha b)+\frac{2C}{(\alpha+\beta)^3}K_0((\alpha+\beta)b)\right.\right.\right.\right.$$

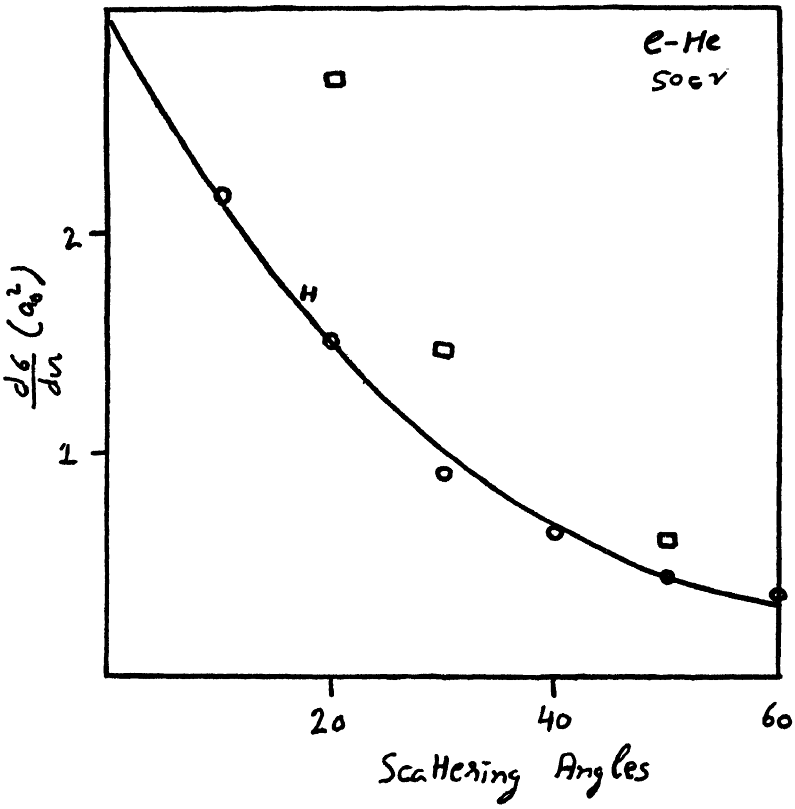

Fig. 1c

$$\left.+\frac{C^2}{(2\beta)^3}K_0(2\beta b)+b\left(\frac{\alpha}{(2\alpha)^3}K_1(2\alpha b)+\frac{C}{(\alpha+\beta)^2}K_1((\alpha+\beta)b)+\frac{C^2\beta}{(2\beta)^3}K_1(2\beta b)\right)\right.$$

$$\left.\left.\left.+\frac{\alpha\pi}{4(b^2+r_0^2)^{3/2}}\right\}\right)-1\right]db \qquad \dots \quad (5)$$

To obtain the scattering amplitudes from (4) and (5) the integrations over b were carried out numerically.

2. Results

The calculated differential cross sections for the scattering of electrons with incident energies of 50,100 and 200 eV from hydrogen and helium atoms (curves

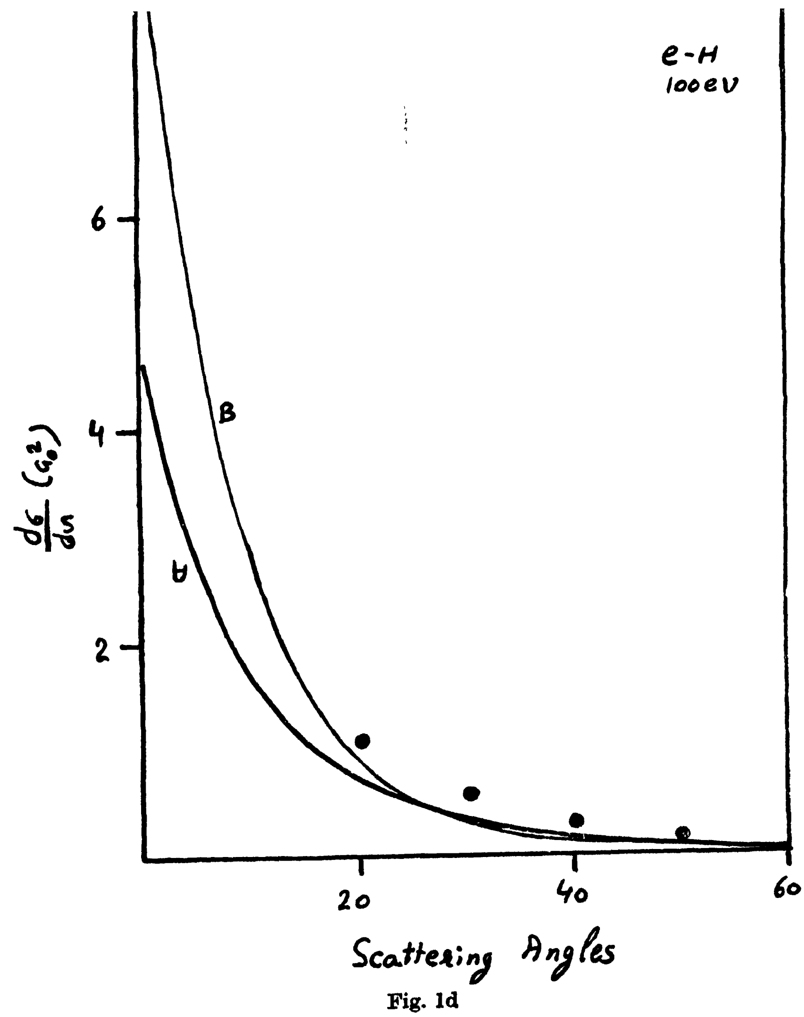

Fig. 1d

A) along with the experimental data of Tubner and Lloyd (1974) in the case of hydrogen and of Crooks and Rudd (1973), Sethuraman, *et al.* (1972) and Vrions

(1968) as normalized by Chamberlain (1970) in the case of helium atom are shown in figure 1. The results of calculations by Saha, Sarkar, and Ghosh (1973) are also shown in the figure (curve B). It can be seen that the results of the present calculations where a simple energy dependent polarization potential has been used for which the integral in the argument of the exponential in (1) can be carried out analytically, are in as fair agreement with experiments as those obtained by

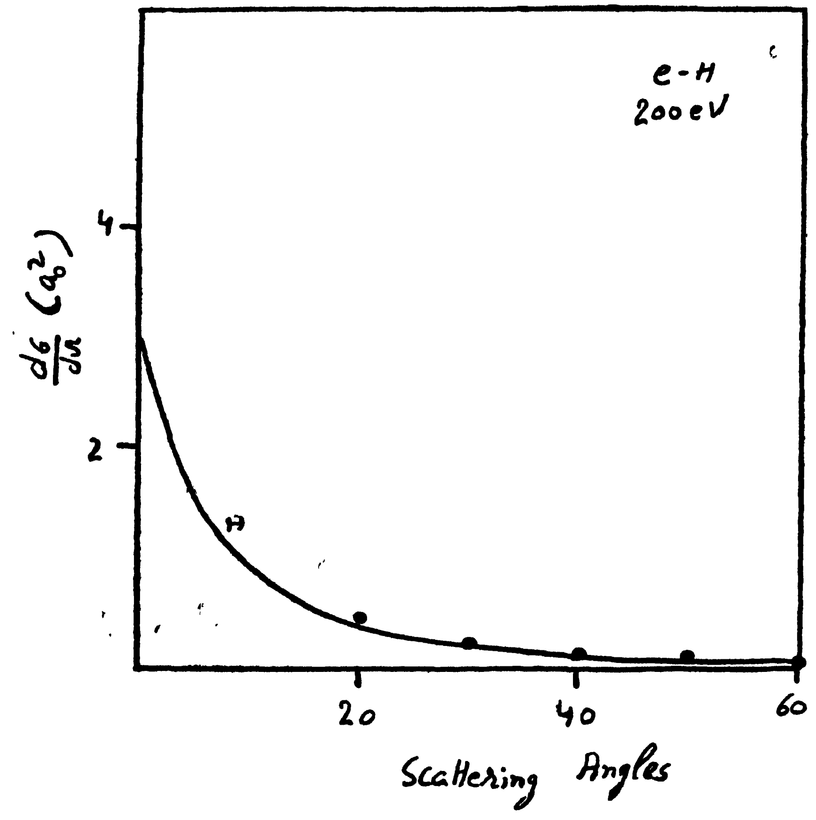

Fig. 1e

Saha *et al.* (1973). Thus, with a polarization potential which takes into account the energy of the incident electron explicitly, the eikonal approximation yields satisfactory description of the low-angle scattering of electrons from hydrogen and helium atoms at intermediate energies. Similar conclusions have been drawn from a more detailed investigation of the polarization and absorption efforts in the e—H and e-He elastic scattering using the eikonal approximation by Byron and Joachain (1974).

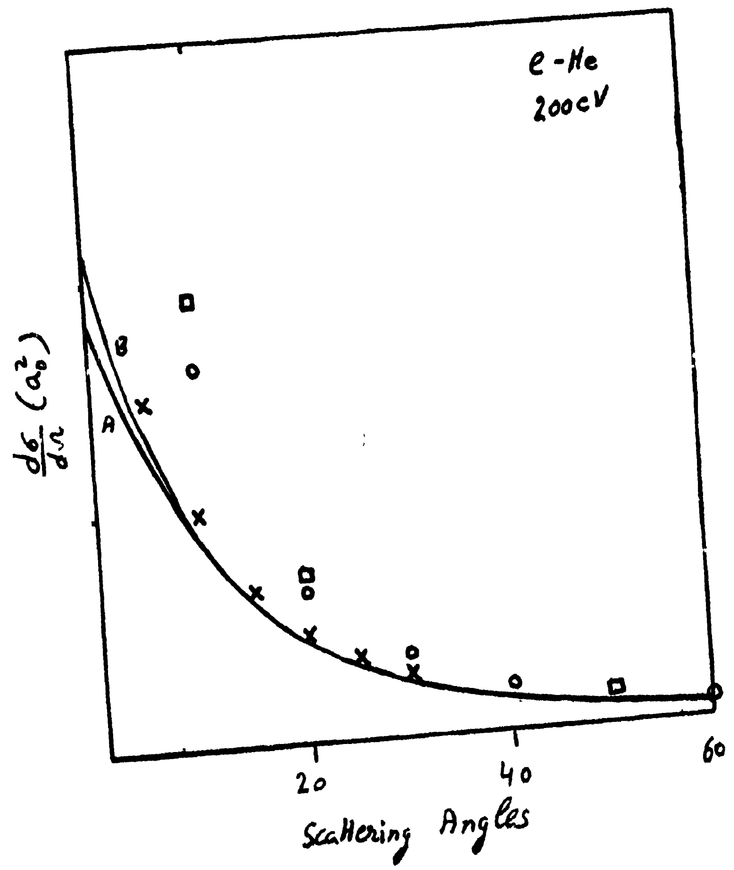

Fig. 1f

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